

Sulfur record of rising and falling marine oxygen and sulfate levels during the Lomagundi event

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Carbonates from approximately 2.3–2.1 billion years ago show markedly positive $\delta^{13}\text{C}$ values commonly reaching and sometimes exceeding +10‰. Traditional interpretation of these positive $\delta^{13}\text{C}$ values favors greatly enhanced organic carbon burial on a global scale, although other researchers have invoked widespread methanogenesis within the sediments. To resolve between these competing models and, more generally, among the mechanisms behind Earth's most dramatic carbon isotope event, we obtained coupled stable isotope data for carbonate carbon and carbonate-associated sulfate (CAS). CAS from the Lomagundi interval shows a narrow range of $\delta^{34}\text{S}$ values and concentrations much like those of Phanerozoic and modern marine carbonate rocks. The $\delta^{34}\text{S}$ values are a close match to those of coeval sulfate evaporites and likely reflect seawater composition. These observations are inconsistent with the idea of diagenetic carbonate formation in the methanic zone. Toward the end of the carbon isotope excursion there is an increase in the $\delta^{34}\text{S}$ values of CAS. We propose that these trends in C and S isotope values track the isotopic evolution of seawater sulfate and reflect an increase in pyrite burial and a crash in the marine sulfate reservoir during ocean deoxygenation in the waning stages of the positive carbon isotope excursion.

Lomagundi excursion | Great Oxidation Event | Precambrian

Fluctuations in organic carbon (OC) burial on geological time scales control the redox state of the ocean–atmosphere system and are linked with major geochemical and biological evolutionary events (1, 2). Carbon isotopes in marine carbonate rocks (limestones and dolostones) are generally assumed to track the balance between OC burial and weathering and are therefore the most widely used proxy for carbon cycling through time (3). Isotopic variations recorded in carbonates throughout Earth's history are typically small ($|\delta^{13}\text{C}| = 5\text{‰}$) and short-lived [<20 million years (Myr)], a pattern attributed to the overall stability of the Earth's biogeochemical carbon cycle (3). However, a significant deviation from this pattern occurred *ca.* 2.3–2.1 billion years (Ga) ago following the initial rise of atmospheric oxygen. Carbonates of this age have markedly positive $\delta^{13}\text{C}$ values often reaching +10‰ and peaking above +20‰ (4–8). These markedly positive values—found in over 15 formations worldwide—are traditionally assumed to track the marine dissolved inorganic carbon (DIC) reservoir and to reflect greatly enhanced organic carbon burial (4–8). It has been estimated that 12–22 times the present atmospheric inventory of oxygen was released because of organic carbon burial during this event, commonly referred to as the Lomagundi excursion (LE) (5).

Alternatively, some researchers have attributed the positive $\delta^{13}\text{C}$ values of Lomagundi-age carbonates to widespread diagenetic carbonate formation—that is, precipitation below the sediment–water interface (e.g., 9, 10). Models suggesting a diagenetic origin for isotopically heavy carbonates often invoke precipitation in the methanic zone of the sediment column to explain the dramatic ^{13}C enrichments. Methanogenesis occurs once energetically more favorable oxidants (e.g., nitrate, Fe and Mn oxides, and sulfate) are exhausted (11). The net result of methanogenesis is a pore-water DIC reservoir with strongly positive isotope

values, provided the isotopically depleted methane is not reoxidized back to DIC (12). Although carbonates formed in the methanic zone can have $\delta^{13}\text{C}$ values larger than +10‰ (13–15), similar to those formed during the LE, carbonates with extreme ^{13}C enrichments are rare in shallow-water settings and are typically found adjacent to carbonates with highly negative carbon isotope values linked to local methane oxidation (e.g., 16).

It is possible that the predominance of positive $\delta^{13}\text{C}$ values seen in carbonate rocks deposited during the LE reflect an unmatched period of methanogenesis close to the sediment–water interface, and a coupling with Earth's redox evolution could explain the historical uniqueness of the event. Specifically, the LE might be a product of progressive oxygenation of the oceans in phase with the initial rise of atmospheric oxygen and with a concomitant shift in the primary locus of biological methanogenesis from the water column to the surface sediments where carbonate minerals then precipitated with the unique ^{13}C enrichments (9). The coincidence between the onset of the carbon isotope excursion and the initial rise of atmospheric oxygen could be consistent with such a model (17). In this case, the LE would reflect a transition in the ocean from a predominantly anoxic to an oxic redox state, at which point extensive methanogenesis occurred near the sediment–water interface, rather than in the water column, and drove carbonate precipitation. Such conditions would have been favored if sulfate concentrations in seawater were still very low.

Contrasting models for the LE that pit diagenetic controls against isotopic shifts in the oceanic DIC pool (tied to organic carbon burial) have profoundly different implications for the chemistry of the oceans, biogeochemical cycling of carbon, and our basic understanding of Precambrian redox history. Because carbon and sulfur cycles are intricately linked on both global and local scales (18), sulfur isotope records of seawater and pore-water sulfate can be used to test between these two models. The $\delta^{34}\text{S}$ values of pore-water sulfate typically increase with depth in sediments due to biological fractionations that favor light sulfur isotopes during bacterial sulfate reduction (BSR). Carbon isotope values of DIC show an initial decrease with depth linked to remineralization of ^{12}C -enriched organic matter with a variety of oxidants (oxygen, Mn^{4+} , Fe^{3+} , nitrate, and sulfate) and then shift to markedly positive values in the methanic zone, where ^{12}C from organic matter is preferentially incorporated into methane (19). Sulfate is structurally substituted into the carbonate lattice during carbonate precipitation (20), and therefore carbonate-associated sulfate (CAS) incorporated during precipitation in the methanic zone should have extremely positive $\delta^{34}\text{S}$ values. Further, because sulfate must be essentially depleted before the onset of appreciable methanogenesis, CAS concentrations in

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methanic carbonates should be very low. We would expect subsequent additional diagenetic overprints, such as meteoric recrystallization, to result in lower, rather than higher, CAS concentrations (e.g., 21).

Within this framework, we present a global survey of new, coupled carbonate-carbon and CAS-sulfur isotope data (i.e., from the same sample) from several Lomagundi-age successions. Beyond this general survey, we have focused in greater detail on the Mcheka Formation of the Lomagundi Group, Zimbabwe; the Nash Fork Formation in Wyoming, United States; and the Lower Alanel Formation in Quebec, Canada. Collectively, these formations span the time interval from the peak to the aftermath of the LE and therefore are particularly well-suited to explore the mechanisms responsible for the termination of the event. Importantly, our data are inconsistent with the idea of carbonate precipitation in the methanic zone as the mechanism behind the unparalleled occurrence of long-lived, highly positive $\delta^{13}\text{C}$ excursion. By default, the onus is put back on organic carbon burial. Accepting that, the LE challenges us to unravel how the marine system sustained unusually high levels of organic carbon burial at the dawn of atmospheric oxygenation.

Materials

We present results from the Lower Alanel, Kona, Lucknow, Silverton, Nash Fork, and Mcheka formations deposited from approximately 2.2 Ga to approximately 2.05 Ga on the Superior, Kaapvaal, Wyoming, and Zimbabwe cratons. The sedimentology, carbon isotope systematics, age constraints, and tectonic setting of the sampled formations have been described previously (4, 22–25). All of the formations were deposited on broad, carbonate platforms and are composed predominantly of fine-grained (micritic) carbonates, but stromatolites and granular units are locally abundant. Similar to other CAS studies (e.g., 26), we have focused on micrite-rich lithologies. Unfortunately, there are no high-resolution age constraints for the units we sampled within a continuous stratigraphic context (Nash Fork, Kona, Mcheka formations), and so it is difficult to estimate their average sedimentation rates with confidence. We therefore estimated average sedimentation rates following the approach of Kah et al. (27). To be conservative in our estimates, we used a very broad range (40–250 m Myr^{-1}). This range is typical of the postcompaction depositional rates over million-year time scales for better constrained Phanerozoic carbonate platform environments (28, 29).

Results

CAS concentrations in carbonates deposited during the LE are higher than those of typical Precambrian carbonates outside the excursion. All our samples from strata deposited during the excursion yield an average CAS concentration of 150 ppm (± 145 ppm, 1 SD). Samples from the Mcheka Formation have an average of 117 ppm (107 ppm, 1 SD), with the uppermost samples typically showing lower concentrations. The Lucknow and Nash Fork formations yield averages of 227 ppm (137 ppm, 1 SD) and 232 ppm (198 ppm, 1 SD), respectively. Carbonates deposited during the final stage of the LE with $\delta^{13}\text{C} \leq 5\text{‰}$ in the Mistassini Basin, Quebec, show lower CAS concentrations compared to those deposited during the peak of the excursion (with an average of 46 ppm; ± 14 ppm, 1 SD). Similarly, Lomagundi CAS concentrations are higher than those typical of carbonates (primarily dolomites) deposited during the later Paleoproterozoic (30, 31), Mesoproterozoic (30, 31), and Neoproterozoic (32) at times when the seawater sulfate reservoir was significantly smaller than that of modern and Phanerozoic oceans (32). Lomagundi CAS concentrations are comparable to those of Paleozoic micritic carbonates (SI Text) (33). The inference, then, is that CAS concentrations in Lomagundi-age carbonates fall in the range of typical marine carbonates that precipitated from waters with a significant sulfate concentration.

CAS from each of the studied formations shows a relatively narrow range of typical marine $\delta^{34}\text{S}$ values (Fig. 1). Combined, CAS from the six formations yields $\delta^{34}\text{S}$ values ranging from +6 to +29‰ (mean +14‰, $n = 105$). These values closely match those from coeval sulfate evaporites (Fig. 1). In the Mcheka

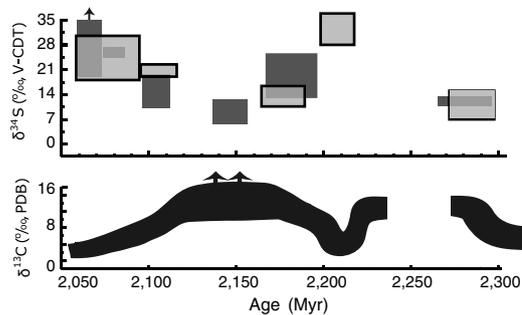


Fig. 1. A generalized $\delta^{13}\text{C}_{\text{carbonate}}$ trend and available sulfate $\delta^{34}\text{S}$ values for the ca. 2.3–2.05-Ga time interval. Light-grey boxes are $\delta^{34}\text{S}$ values for sulfate evaporite (gypsum and anhydrite), and dark-grey boxes are $\delta^{34}\text{S}_{\text{CAS}}$ data from this study. Note that $\delta^{34}\text{S}_{\text{CAS}}$ values are essentially the same as those of coeval sulfate evaporites, suggesting that they record the seawater sulfur isotope composition. There is an antithetic relationship between carbonate $\delta^{13}\text{C}$ and sulfate $\delta^{34}\text{S}$ values, which is particularly prominent on the falling limb of the Lomagundi carbon isotope excursion (SI Text for additional figure information).

Formation, the falling limb of the $\delta^{13}\text{C}$ excursion is marked by a systematic upsection increase in $\delta^{34}\text{S}_{\text{CAS}}$ values (Figs. 2 and 3A). There is also an inverse $\delta^{13}\text{C}_{\text{carb}} - \delta^{34}\text{S}_{\text{CAS}}$ relationship in the Nash Fork Formation, although it is less well-developed. $\delta^{34}\text{S}_{\text{CAS}}$ values from carbonates of the Mistassini Basin, deposited during the final stages of the Lomagundi excursion (averaging 29‰, maximum 31‰), and in its aftermath (averaging 33‰, maximum 47‰), are higher than those typical of the LE. These results are consistent with the general trend we see for the event: more positive $\delta^{34}\text{S}$ values with decreasing $\delta^{13}\text{C}$ values.

Diagenetic Influence on Carbonate Precipitation

A coupled C–S isotope approach can be used to test for a diagenetic influence on carbonate precipitation. Sulfate is structurally substituted into the carbonate lattice during carbonate precipitation, and the concentration of CAS is proportional to ambient sulfate concentrations during carbonate precipitation (20, 34). How CAS concentration specifically scales with seawater sulfate concentration is not well-known and can be influenced by a number of factors (e.g., temperature, mineralogy, and crystal growth rate). Additionally, vital effects can also be important in biogenic phases. However, initial CAS concentrations do, in a more straightforward way, scale with seawater concentrations when abiotic precipitation dominates, as in the case with the samples for this study. Diagenesis can change primary CAS concentrations (21), and the effects of dolomitization on CAS are poorly constrained (35). Nevertheless, although CAS concentrations

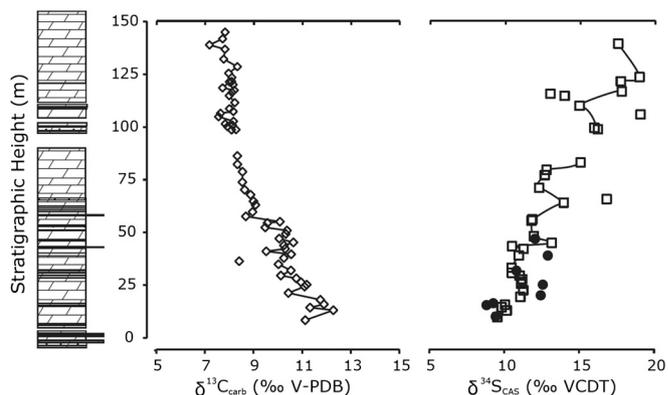


Fig. 2. Carbonate $\delta^{13}\text{C}$ and $\delta^{34}\text{S}_{\text{CAS}}$ stratigraphic trends in the Mcheka Formation, Zimbabwe. The black circles on the $\delta^{34}\text{S}_{\text{CAS}}$ plot are for a duplicate section approximately 200 m along the strike. $\delta^{34}\text{S}_{\text{CAS}}$ values systematically increase as carbonate $\delta^{13}\text{C}$ values systematically decrease up-section in the Mcheka Formation.

Paleoproterozoic. Isotope mass balance arguments (49) suggest that pyrite dominated the sedimentary sulfur burial flux until the Phanerozoic, when the development of bioturbation significantly changed the global S cycle, and burial of sulfate as gypsum and anhydrite became quantitatively important (49). Therefore, long-term marine sulfate $\delta^{34}\text{S}$ isotopic shifts in the Phanerozoic—but not in the Paleoproterozoic—were strongly influenced by changes in the ratio of reduced to oxidized sulfur buried in marine systems.

The observed rise in sulfate $\delta^{34}\text{S}$ values and the inverse C–S isotope relationship during the falling limb of the LE can be linked to increased pyrite burial during a global deoxygenation event. Increased pyrite burial, without a corresponding decrease in gypsum burial, at the end of the LE would have triggered a dramatic drop in the size of the marine sulfate reservoir and an increase in the marine sulfate $\delta^{34}\text{S}$ value. If the markedly positive carbonate $\delta^{13}\text{C}$ values that characterize the LE are linked to enhanced organic carbon burial (cf. 5), it would follow that there would be a drop in the oxygen levels of the ocean–atmosphere system (caused by lower organic carbon burial and a smaller O_2 flux) at the end of the LE. The switch to a more reducing ocean–atmosphere system may also be the consequence of oxidation of uplifted organic carbon-rich rocks buried during the early stages of the LE (50). A global increase in pyrite burial should accompany the switch to a more reducing ocean—because sulfide reoxidation will decrease as marine anoxia becomes more expansive (e.g., 51). Given this framework, the rise in sulfate $\delta^{34}\text{S}$ values during the end of the LE reflects a drop in oceanic oxygen levels that promoted enhanced pyrite burial (and thus more burial of isotopically light sulfur). At the core of this model is the requirement that large swaths of the ocean were ventilated during the LE and became less oxygenated in its wake.

The observed inverse C–S relationship between sulfate $\delta^{34}\text{S}$ and carbonate $\delta^{13}\text{C}$ values in the LE may also be tied to decreases in the extent of continental pyrite oxidation and concomitantly in the magnitude of the continental sulfate flux (52). Limited terrestrial sulfide oxidation in the Archean would have led to higher-than-modern levels of reduced sulfur in the upper crust available for terrestrial weathering (52, 53). With an anoxic atmosphere, the majority of sulfides during weathering would be transported from continental settings to shallow marine environments without being oxidized—leading to burial of detrital pyrites. It has been proposed that first exposure of upper continental crust developed under essentially anoxic conditions to an oxygenated world would fuel intense pyrite oxidation, enhanced sulfate delivery to the oceans, and growth of the marine sulfate reservoir (52, 53). A larger marine sulfate reservoir and a fully oxidative continental sulfur cycle is likely to yield a decrease in the ratio of sulfur buried on the continental margin relative to deep-sea environments. This shift is significant because sediments on the margin have a much higher potential than deep-sea environments to escape subduction and instead be exhumed and subjected to continental weathering. On geologic time scales (tectonic-recycling time scales), increasing deep-sea sulfur burial may result in a decrease in the average amount of sulfide present in exhumed marine sedimentary rocks. The termination of the LE is about one to two sedimentary rock half-lives (somewhere between 100 and 300 Myr—e.g., ref. 54) after the rise of atmospheric oxygen, which is the time required for tectonic processes to replace Archean pyrite-rich sedimentary rocks with the less pyrite-rich sedimentary rocks formed in the wake of the Great Oxidation Event (53). Therefore, it is possible that the sulfur isotope behavior observed at the end of the LE corresponded with a decrease in the continental sulfate flux, which (along with increased pyrite burial) could also drive a shift to more positive sulfate $\delta^{34}\text{S}$ values.

This decrease in the amount of sulfide present in the upper crust may also be linked to the anomalous carbonate $\delta^{13}\text{C}$ values

that characterize the LE (53). Increased pyrite oxidation in continental weathering environments would have increased acid generation, which could have fueled increased apatite dissolution and amplified the continental phosphorus flux to the oceans. A stronger continental phosphate flux would have enhanced organic carbon burial on a global scale, ultimately leading to the shift to positive carbonate $\delta^{13}\text{C}$ values (53). High rates of sulfide oxidation would have also increased the flux of some bioessential metals (e.g., molybdenum), which may have been biolimiting up to that point (e.g., 55).

A simple, global S cycle box modeling approach (e.g., 33, 56) can be used to evaluate the relative roles that increased pyrite burial and a decreased continental sulfate flux played in controlling sulfate $\delta^{34}\text{S}$ trends during the tail end of the LE (*SI Text* for model description). A strong increase in pyrite burial (approximately two- to threefold increase from the global modern pyrite burial flux) is needed to reproduce the observed shift in $\delta^{34}\text{S}$ values at the end of the LE (*SI Text*). This shift in burial is equivalent to estimates for increased burial during Phanerozoic ocean anoxic events (OAEs) (e.g., 33), suggesting relatively dramatic shifts in sulfur burial and the global redox landscape during the end of the LE. Given a reasonable set of model parameters (*SI Text*), it is not possible to drive the rise in sulfate $\delta^{34}\text{S}$ values observed at the tail end of the LE exclusively through decreases in the continental sulfate flux. However, it is possible to reproduce the observed trend via a decrease from 115% to 100% of the modern continental sulfate input, as long as there is also a correspondingly strong (three- to fourfold) increase in the amount of marine pyrite burial. Use of much higher continental sulfate inputs (e.g., 130% of modern) results in unrealistically high sulfate concentrations or requires unreasonable pyrite burial fluxes and fractionation factors (*SI Text*). Implicit in this modeling approach is that pyrite dominated the marine S burial flux in the Paleoproterozoic (cf. 49). A key question is if an approximately 10% to 20% increase in the amount of weathering-mediated pyrite oxidation during the peak of the LE would be able to alter significantly the continental phosphorus flux and drive enhanced organic carbon burial (53).

Conclusions

Approximately 2.3- to 2.1-Ga carbonate rocks have markedly positive $\delta^{13}\text{C}$ values, commonly reaching beyond +10‰. Because C and S isotopes of dissolved inorganic carbon and sulfate follow predictable trends in diagenetic settings, we can use these isotopic systems to identify or rule out diagenetic carbonate precipitation. Specifically, sulfate $\delta^{34}\text{S}$ values increase with burial depth because of biological fractionations associated with BSR, whereas DIC isotope values show an initial decrease followed by a shift to markedly positive values in the methanic zone (16). In contrast to the trend predicted for early diagenesis, we found a narrow range of moderate S isotope values in each of the studied carbonate units deposited between approximately 2.3 and 2.1 Ga that is essentially the same as that of the coeval sulfate evaporites, which is inconsistent with carbonate formation in the methanic zone. Lomagundi-excursion carbonates appear to record seawater C and S isotope signatures, and can thus contribute to our understanding of Paleoproterozoic biogeochemical cycles.

High [CAS] and relatively low variability of CAS $\delta^{34}\text{S}$ values in LE carbonates relative to younger Proterozoic equivalents point to a large coeval marine sulfate reservoir followed by a decrease in seawater concentrations. The falling limb of the Lomagundi excursion is marked by an increase in $\delta^{34}\text{S}_{\text{CAS}}$ and a strong decrease in [CAS]. We propose that these changes reflect an increase in pyrite burial and a crash in the marine sulfate reservoir during ocean deoxygenation in the waning stages of the positive carbon isotope excursion. A simple global mass balance model for sulfur suggests that there was at least a two- to threefold increase in global pyrite burial at the end of the LE—equiva-

lent to the magnitude of increases associated with the Phanerozoic OAEs. This large shift in pyrite burial suggests the end of the LE was marked by a significant redox shift and points toward a dramatic rise and fall in oxygen levels in the ocean atmosphere system during the Paleoproterozoic. It seems likely that deoxygenation of the ocean–atmosphere system at the end of the LE was an inevitable consequence of decreased organic carbon burial and parallel O₂ loss via oxidation of exhumed organic carbon-rich sediments buried during the peak of the LE. There is mounting evidence that, in contrast to the traditional view of a unidirectional oxygen rise, there was significant variability in the redox state of Earth's surface during the Precambrian (50, 53).

Methods

We used a CAS extraction method modified from traditional approaches to ensure that sulfide oxidation during extraction is negligible. In summary, 20 to 100 g of powder was exposed to successive NaCl and H₂O₂ treatments with two distilled-water rinses following each step. The intent is to remove sulfates and sulfides (foremost HCl-soluble iron monosulfides) that might skew the primary CAS record. The powders were then dissolved through slow addition of a 5% SnCl₂ 4N HCl solution. Addition of SnCl₂, a reductant, prevented sulfide oxidation by reaction with any Fe(III) liberated during the HCl addition, thus minimizing contamination to the CAS signal. Liberated

primary CAS was precipitated through addition of BaCl to induce barite precipitation. Sulfur isotope measurements were made after on-line barite combustion using a ThermoFinnigan DeltaV Plus continuous-flow stable isotope ratio mass spectrometer at University of California, Riverside. Reproducibility was better than 0.2‰ based on single-run and long-term standard monitoring. CAS concentrations were measured using an Agilent inductively coupled plasmonic MS in the Xe collision-cell mode to reduce oxide interferences, and reproducibility was better than 88%. We estimated Paleoproterozoic sulfate concentrations based on maximum $\delta^{34}\text{S}_{\text{CAS}}$ variability following the approach in ref. 36 for the Mcheka Formation, and using the approach in ref. 27 for the Kona Dolomite. Error bars reflect the range of estimates for the duration the examined sequences. Global sulfur cycle box modeling was done following the approach in ref. 32. Model parameters and sensitivity tests are presented in refs. 32 and 53 and *SI Text*.

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Supporting Information

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SI Text

Global Sulfur Cycle Model. We used a widely employed global sulfur cycle box modeling approach (e.g., 1–3) to explore the dynamics and significance of the carbonate-associated sulfate (CAS) isotope record at the end of the Lomagundi excursion (LE). Gill et al. (2) and Kurtz et al. (4) recently described the modeling approach in detail, so we only provide an overview. We used the following expression to mimic the isotopic change of the global marine sulfate reservoir:

$$\frac{\partial \delta_0}{\partial t} = \frac{F_W(\delta_W - \delta_0) - F_{py}\Delta S}{M_0}$$

where M_0 and δ_0 are the amount of sulfate S in the ocean reservoir and its isotopic composition, respectively. The input to the ocean, F_W , includes sulfur fluxes to the marine system from weathering and magmatic processes, and is assigned a single, average isotopic composition (δ_W). F_{py} is the pyrite burial flux and ΔS is the mean fractionation from oceanic sulfate caused by bacterial sulfate reduction and pyrite formation. Consistent with the sulfide $\delta^{34}\text{S}$ record (e.g., 5), we have used a lower $\Delta^{34}\text{S}$ value than is typically used for Phanerozoic modeling work (Fig. S1), and we have assumed a constant $\Delta^{34}\text{S}$ throughout the LE. Initial and nonvarying boundary conditions (Fig. S1) are similar to those used in Phanerozoic sulfur cycle models (e.g., 2). The one exception is that evaporate burial, which does not have a significant associated isotopic fractionation, was held below 15% of the modern flux. Estimates of marine sulfur concentrations, along with the reduced to oxidized sulfur ratio of the marine burial flux during the LE are discussed in the main text. We constructed the model using STELLA™ modeling software and employed a forward modeling approach—varying key boundary conditions for the sulfur cycle (Fig. S2), in order to best recreate the observed sulfur isotopic profile.

We have modeled the observed rise in marine sulfate $\delta^{34}\text{S}$ values during the falling limb of the LE. More specifically, we modeled a rise in the $\delta^{34}\text{S}$ value of marine sulfate from approximately 13‰ to approximately 28‰ over 50 million years (Myr). The observed isotopic shift may have occurred more rapidly than 50 Myr (estimated to have occurred between 30–50 Myr; Fig. 2). However, given that our conclusion is that this isotope shift represents a significant geochemical perturbation, this long timespan is conservative. We suggest the data are best reproduced with a strong (2.7-fold) increase in pyrite burial (relative to the modern global burial flux), a modern continental sulfate flux, a starting marine sulfate concentration of 7 mM, and mean $\Delta^{34}\text{S}$ value of -17 ‰ transiently increasing to -21 ‰ (Fig. S1). The sulfate $\delta^{34}\text{S}$ values can also be reproduced with an elevated continental sulfate flux. However, with a larger continental sulfate

flux, an increase in the global pyrite burial flux is needed to reproduce the rise in $\delta^{34}\text{S}$ values at the tail end of the LE. For instance, a 3.2-fold increase in the global pyrite burial flux relative to the modern is needed given a transient decrease from 115% to 100% of the modern continental sulfate flux over the 50-Myr period. Model runs using very elevated continental sulfate fluxes (≥ 120 % of the modern flux), without inducing extensive gypsum burial (at least 50% modern evaporate burial), yield very high (>20 mM) marine sulfate concentrations. Marine sulfate concentrations above 20 mM are inconsistent with available estimates for the size of the marine sulfate reservoir in the mid-Paleoproterozoic (see main text).

Sensitivity tests for key model variables are shown in Fig. S2. The model is sensitive enough to pyrite burial (Fig. S2A) that the percent increase in pyrite burial can be estimated within a relatively narrow range (an increase in pyrite burial to >2.15 and <3.15 times the modern flux). However, as noted above, if the observed rise in carbonate-associated sulfate (CAS) $\delta^{34}\text{S}$ values occurred over a shorter time period than estimated, larger increases in pyrite burial will be needed (Fig. S2A). The model is also very sensitive to the magnitude of the continental weathering flux (all other parameters being held constant)—15% changes in the magnitude of the continental sulfate flux lead to large (>5 mM) changes in the peak marine sulfate concentrations (Fig. S2B). The starting sulfate concentration makes little difference on the trajectory of the isotopic profile (Fig. S2C), but does affect the peak sulfate concentration and the sulfate concentration at the end of the event. In contrast, strong (>10 ‰) shifts in the ΔS value can significantly decrease (>10 Myr) the time needed to induce the observed isotopic shift, but varying the ΔS value has no effect on the sulfate concentrations (Fig. S2D). However, there is not current evidence that global mean pyrite $\delta^{34}\text{S}$ values varied substantially throughout the mid-Paleoproterozoic (e.g., 5).

It has been proposed that an increase in hydrothermal activity can cause an antithetic relationship in marine sulfate $\delta^{34}\text{S}$ and carbonate $\delta^{13}\text{C}$ records, with light $\delta^{34}\text{S}$ values being linked to strong mantle-derived sulfur fluxes (6, 7). Although the end of the Lomagundi excursion coincides with the breakup of Kenorland and, likely, enhanced hydrothermal activity, we note that the pattern predicted by this model is opposite from what we observe in the rock record (Fig. 2). A shift to positive carbon isotope values is expected with enhanced hydrothermal activity and downward trend in S isotope values (6, 7). Given this framework, any changes in the hydrothermal S flux during the LE would require more pronounced shifts in pyrite burial at the end of the LE than we have predicted. We have not varied the hydrothermal sulfur flux in the model runs, which renders our conclusions conservative.

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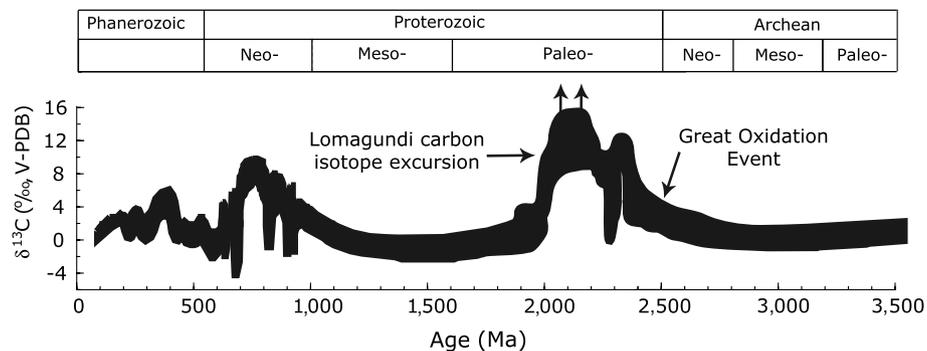


Fig. S3. Generalized carbonate-carbon isotope curve through time. The Lomagundi positive carbon isotope excursion is the longest and largest deviation from the near-zero $\delta^{13}\text{C}$ values typical of carbonates throughout Earth's history. The onset of the Lomagundi excursion closely follows the initial rise in atmospheric oxygen (cf. 1). Based on the global pattern of carbon isotope values in Paleoproterozoic marine carbonates, the Lomagundi excursion likely encompassed at least two separate intervals of markedly positive $\delta^{13}\text{C}$ values. Modified from ref. 2.

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2 Karhu JA (1999) *Encyclopedia of Geochemistry*, eds Marshall CP, Fairbridge RW (Kluwer Academic Publishers, Boston), pp 67–73.

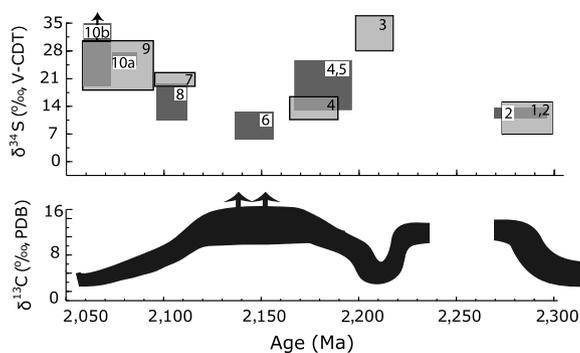


Fig. S4. A generalized $\delta^{13}\text{C}_{\text{carbonate}}$ trend and available sulfate $\delta^{34}\text{S}$ values for the ca. 2.3–2.05-billion-year (Ga) time interval. Light-grey boxes are $\delta^{34}\text{S}$ values for sulfate evaporite (gypsum and anhydrite), and dark-grey boxes are $\delta^{34}\text{S}_{\text{CAS}}$ data from this study. The $\delta^{13}\text{C}_{\text{carbonate}}$ curve is modified from ref. 1, and the compilation of sulfate evaporite S isotope values is from ref. 2 (also presented in Table S4). The $\delta^{34}\text{S}_{\text{CAS}}$ values are from this study. The ages of the units (and the duration) is based on the available constraints from radiometric ages (see ref. 2) and the carbonate-carbon isotope data, relative to the idealized carbon isotope curve. 1, Gordon Lake Formation; 2, Kona Dolomite; 3, Lower Umba Formation; 4, Lucknow Formation; 5, Silverton Formation; 6, Nash Fork; 7, Delwara Formation and Jhamarkotra Formation; 8, Mcheka Formation; 9, Fedorovka Formation; 10a, Lower Albabel Formation (Lomagundi Excursion); 10b, Lower Albabel Formation (post Lomagundi Excursion)

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Eon/era	Age (Myr)	Estimate of marine [sulfate] (mM)	Basis for estimate	Reference
Mid-Proterozoic	18,00–700	<1	Maximum sulfur isotope fractionation during bacterial sulfate reduction based on the temporal isotopic record of pyrite and sulfate	Canfield et al. (7)
Archean	3,800–2,500	<0.2	Maximum sulfur isotope fractionation during bacterial sulfate reduction based on the temporal isotopic record of pyrite and sulfate	Habicht et al. (8)

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Table S4. Sulfur isotope data from evaporites deposited during the Lomagundi excursion

Name of unit (location)	Age (Ga)	Type of evaporite	$\delta^{13}\text{C}$ (‰)	$\delta^{34}\text{S}$ (‰)	Reference
Gordon Lake Formation, Huronian Supergroup (Lake Huron, Canada)	ca. 2.3–2.22	Silicified and pristine anhydrite and gypsum nodules and layers	5.0–8.2	11.7–15.6	Cameron (1), Chandler (2), Bennett et al. (3), Bekker et al. (4)
Kona Dolomite, Chocology Group (Michigan, USA)	ca. 2.3–2.22	Pseudomorphs after gypsum and anhydrite	5.0–9.5	11.4–16.0	Bekker et al. (4), Taylor (5), Clark (6), Wohlabaugh (7), Hemzacek et al. (8), Hemzacek (9), Perry et al. (10), Feng (11), Genest (12)
Lower Umba Formation, Lower Jatulian Group (Imandra–Varzuga Belt, Kola Peninsula, Russia)	ca. 2.2	Barite beds	2.3–6.7	27.8–34.2	Melezhik and Fetisova (13), Grinenko et al. (14), Melezhik and Fallick (15)
Lucknow Formation, Postmasburg Group (South Africa)	ca. 2.15	Molds and quartz pseudomorphs after gypsum and anhydrite	8.4–11.3	9.2–14.0	Master et al. (16), Swart (17), Schröder et al. (18)
Delwara Formation and Jhamarkotra Formation, Aravalli Group (Rajasthan, India)	ca. 2.1	Barite layers	5.1–11.1	17.1–21.2	Deb et al. (19), Sreenivas et al. (20)
Fedorovka Formation (Aldan Shield, Siberia, Russia)	ca. 2.1	Anhydrite layers and veins	–1.7–5.5	up to 32.1	Zolotarev et al. (21), Velikoslavinsky et al. (22), Guliy and Wada (23)

Table after Bekker et al. (4) and Schröder et al. (16).

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